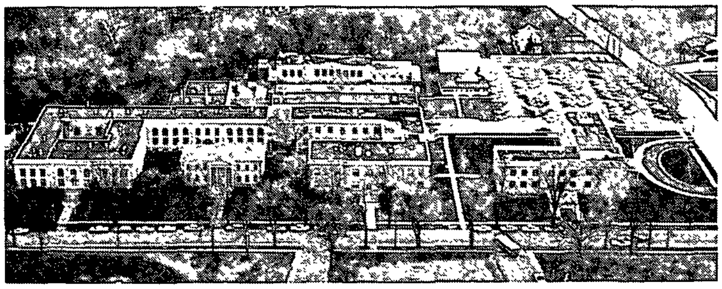

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ABSTRACT

The tensile strength characteristics of white spruce fibers separated at three different temperatures were measured both before and after classifying them into fractions differing in average fiber size. In addition, loblolly pine fibers separated at a single temperature were similarly evaluated. It was observed that fibers separated at 160°C are stronger than those sep-separated at 120°C and that there are marked differences between average strengths of fibers from different size fractions of the same pulp. Compared to white spruce mechanical pulp fibers, those from loblolly pine are slightly weaker. They also differ from the spruce fibers inasmuch as their strength is similar in all size fractions. It was concluded that the fiber separation phase of mechanical pulping results in fiber weakening to an extent that is directly related to the prevailing resistance to separation.

INTRODUCTION

The mechanical properties of paper are determined by the properties of its component fibers and the bonds between them. In 1958 Van den Akker demonstrated that sheet strength is determined by both interfiber bond strength and fiber strength, not just by the former (1). Since then, considerable research has been directed toward the goal of characterizing the mechanical properties of individual pulp fibers and understanding the factors affecting them.

Despite the increased research activity, interest in the mechanical behavior of mechanical pulp fibers has remained low. The reason is the well known inability of such pulps to form strong interfiber bonds and the related assumption that bond strength, not fiber strength, is the "weak link" that determines the strength of the sheet. With the advent of chemical treatments that make it possible to achieve high levels of interfiber bonding, however, this assumption must be questioned. An investigation of the tensile properties of mechanical pulp fibers is thus timely. It is also necessary to define conditions for fiber separation that will provide the best raw material for subsequent development of bonding potential by chemical and/or mechanical treatment.

The objectives of the present study were to characterize the behavior of unrefined mechanical pulp fibers in axial tension, to determine the effect of changing the temperature of fiber separation on that behavior, and to compare fibers from two different species, white spruce and loblolly pine. The choice of unrefined (barely separated) fibers was predicated on the desirability of separately studying the two different processes that occur during mechanical pulping: fiber separation and surface development. In addition to facilitating an understanding of the entire process, this approach allows for the possibility that bonding ability can be developed by means other than the mechanical treatment that immediately follows fiber separation in disc refiners. For optimal use of such a process it would be important to know how to separate, but not refine, fibers with minimum damage to their tensile strength characteristics. The study of temperature effects is an important step in this direction. Comparing two species of divergent morphology and pulping behavior should shed light on the reasons for the latter and extends the applicability of the results.

Earlier studies of the strengths of individual pulp fibers have been directed mainly toward understanding the behavior of chemical pulps (2-7). In general, they have shown that fibers are extremely variable with respect to tensile stress-strain characteristics, and that their breaking stresses lie in the range 40-130 kg/mm^2. Page and coworkers (5,8,9) have interpreted the literature and their own data in terms of three dominant factors: secondary wall fibril angle, structural defects and cellulose content. On this basis, it may be expected that the strength of mechanical pulp fibers from a given wood source will be controlled by defects, at least some of which are introduced during the fiber separation and surface development phases of the pulping process.

In this light, it may be hypothesized that the greater the resistance to fiber separation, the greater is the amount of energy that a given fiber must absorb before becoming separated from its neighbors, and the greater is the number of defects that will be introduced into its structure as a result of that energy absorption. A similar effect on fiber length may be postulated, since a break may be viewed as the ultimate defect. It follows that, if the hypothesis is true, reducing the resistance to fiber separation by increasing the fiberization temperature will increase fiber strength as well as fiber length. It also follows that fiberization at a given temperature will yield fiber fragments that have lower strength than the intact fibers produced at the same time because the fragments will have been weakened as a result of the same events that shortened them. The present study was designed to test this hypothesis by comparing the strengths of fibers separated at different temperatures and comparing the strengths of fibers in different size categories produced at the same temperature.

The experimental work consisted of the preparation and testing of eight fiber samples, six from white spruce and two from loblolly pine. All were made at very high freeness levels so that any observed effects could be associated with fiber separation, uncomplicated by the occurrence of appreciable refining. Spruce pulps were made under each of three different sets of conditions, differing principally with respect to temperature. One corresponded to atmospheric refiner mechanical pulping, with no chip preheating. The second corresponded to thermomechanical pulping, with preheating of the chips at 120°C, and the third to fiber separation after preheating the chips to 160°C, a temperature well above the glass transition point of lignin. All of the spruce pulps were prepared in a Sunds Defibrator two stage pilot thermomechanical refining system, equipped with a 300CD primary refiner fitted with flat plates only. The pine pulp was prepared in the laboratory at 120°C in an Asplund mill, a pressurized batch fiberizer. Further details concerning preparation of the fiber samples may be found in the experimental section.

Each batch of fiber was sampled directly and some were also sampled again after separation into size fractions in a Bauer-McNett classifier. A total of 20 samples were evaluated, each consisting of approximately 50 individual fibers or fiber fragments. (An exception was the first of the two samples prepared from spruce at 120°C, for which 103 fibers were tested, owing to higher than usual variability in this sample.) All fibers and fiber fragments longer than about 1.3 mm in each sample were tested. Fibers were dried on a Teflon treated glass plate and glued to mounting pins with an epoxy adhesive. Testing was conducted at 23°C and 50% relative humidity on the fiber load-elongation recorder previously described by Hardacker (10).

After each rupture, one of the remaining fiber segments was cut from its pin and placed in the IPC Compacted Fiber Dimension Apparatus (11) for cross-sectional area (CSA) measurement. This instrument laterally compacts the fiber under a high enough stress (5-50 kg/mm^2) to collapse the lumen and any other voids in the cell wall visible at about 120X magnification. Measurement of the width and double wall thickness of the resulting compacted fiber segment permits calculation of the CSA of the solid material in the wall. Breaking stress was then determined for each fiber by dividing its breaking load by its CSA.

Statistical Analysis

For each fiber tested, measured values of thirteen variables were recorded. Five of these were qualitative or semiquantitative discrete variables (stress-strain curve type, break location, etc.), four were fiber dimensions (length, width, thickness and cross-sectional area) and four were stress-strain curve parameters (initial modulus, breaking load, breaking stress and breaking strain). All possible pairwise correlations of these variables were examined by generating the correlation matrix for each sample. The frequency distribution of each variable within each sample was also examined.

It soon became apparent that none of the quantitative variables was normally distributed. One indication of this was that many of the observed frequency distributions were skewed to the right; another was that most displayed correlations between the mean and the standard deviation. Since both observations are consistent with the assumption that the data are from log normal populations, data were converted to their logarithms and reanalyzed. The logarithms were more nearly normally distributed, although in some cases the transformation introduced negative skewness.

In addition to calculating the mean and variance for each variable within each sample, a one-way analysis of variance was performed for all samples simultaneously. This afforded a pooled error estimate that was used to calculate a 95% confidence interval for each mean and a "least significant difference," the amount by which two means must differ before they can be declared different at the 95% confidence level. Both values are given in the footnotes to the data tables.

For data presentation, the logarithmic averages were transformed back to the linear scale. A consequence of the log normal distribution is that the error is better expressed as a percentage of the mean than as an absolute value. Another is that the mean values are slightly lower than they would be if the normal distribution had been assumed.

RESULTS AND DISCUSSION

Fiber Integrity and Dimensions

Integrity - Table I gives the percentage of testable fibers and fragments (longer than about 1.3 mm) in each category that were whole fibers and the number that were fragments with either one or two broken ends. Among the whole pulps, about half of the spruce fibers and a third of the pine fibers were intact, while in the fractions the percentage of intact fibers varied from 60-85 in the 14 mesh fractions to 20-45 in the 48 mesh fractions. Fibers with two broken ends were virtually absent in the former, but represented up to 15% of the number in the latter fractions. Thus, the samples tested represented a variety of degrees of fiber breakage.

Table I. Classification of fibers tested into whole fibers and fragments having either one or two broken ends (as percentages of the total number tested).

Species	Fiberizing Conditions	No. of Broken Ends	Whole Pulps	14-Mesh Fraction	28-Mesh Fraction	48-Mesh Fraction
Spruce	Atmospheric	0	50	85	58	19
		1	45	15	40	66
		2	5	0	2	15
	120°C	0	45	57	65	20
		1	45	41	31	66
		2	10	2	4	14
	160°C	0	59	82	65	45
		1	36	18	31	53
		2	5	0	4	2
Pine	120°C	0	32	70	48	41
		1	58	28	47	53
		2	10	2	5	6

Fiber Dimensions - The mean lengths of the fibers and fiber fragments varied from 1.8 to 3.9 mm, as shown in Table II. In a rough sense, they are inversely proportional to the number of broken ends in Table I, an observation which is consistent with the assumption that the lengths of the fibers tested was controlled by breakage in the refiner rather than by natural variation.

The compacted width and thickness of fiber segments after testing both decreased as the fiber length decreased; the result was a strong positive correlation between fiber length and compacted segment CSA (Table III and Figure 1). These trends were also apparent for individual fibers within samples. Since length is controlled by breakage, this may be interpreted to mean that more slender fibers are more likely to be broken during fiberization in the refiner.

Table II. Mean lengths (in mm) of the fibers tested.

Species	Fiberizing Conditions	Fiber Sample	Whole Sample	14-Mesh Fraction	28-Mesh Fraction	48-Mesh Fraction
Spruce	Atmospheric	1	2.30	3.18	2.57	1.79
		2	2.19			
	120°C	1	2.58	3.34	2.80	1.91
		2	2.52			
	160°C	1	2.44	3.17	2.57	1.94
		2	2.61			
Pine	120°C	1	2.55	3.87	3.28	2.34
		2			3.08	

Notes: a. Figures shown correspond to arithmetic means of the logarithms of the observed fiber lengths.
b. Each of the means shown has a 95% confidence interval of plus or minus approximately 6.6%.
c. Two means differ significantly if the larger is more than 10% greater than the smaller.

Table III. Mean compacted fiber cross-sectional areas, μm^2.

Species	Fiberizing Conditions	Fiber Sample	Whole Sample	14-Mesh Fraction	28-Mesh Fraction	48-Mesh Fraction
Spruce	Atmospheric	1	184	220	167	151
		2	169			
	120°C	1	186	235	198	144
		2	167			
	160°C	1	167	228	186	130
		2	198			
Pine	120°C	1	334	456	372	327
		2			376	

Notes: a. Figures shown correspond to arithmetic means of the logarithms of the observed fiber cross-sectional areas.
b. Each of the means shown has a 95% confidence interval of plus or minus approximately 13%.
c. Two means differ significantly if the larger is more than 10% greater than the smaller.

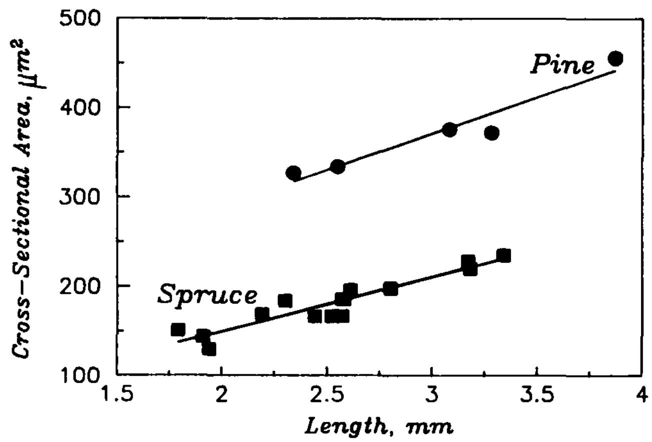

Fig. 1. Relationships between lengths of fibers and fiber fragments and their cross-sectional areas for white spruce and loblolly pine mechanical pulp fibers.

Tensile Testing: General Observations

Load-Elongation Curve Shapes - All of the curve types observed by Hardacker (10) in testing chemical pulp fibers were observed in the present work. The majority, however, were either straight or concave downward.

Fiber Twisting - Although the fibers were slightly restrained during drying by adhesion to the Teflon treated glass plate, some of them developed twists. The number of half-twists in each fiber was noted, but little correlation between this number and any of the mechanical properties measured was observed. The twisted fibers exhibited slightly higher elongation at rupture and in some cases tended to have lower breaking load. The latter effect was a result of a correlation between slenderness and tendency to twist; the more slender fibers were more likely to twist and also had lower breaking loads at the same breaking stress because of their smaller CSA.

Breaks at the Glue Line - About half of the fibers tested broke at the glue line rather than elsewhere in the test span. This caused some concern and prompted a careful statistical analysis to detect differences attributable to this behavior. In 18 of the 20 samples tested there was no significant difference between the strengths of fibers that broke at the glue line and those that broke elsewhere. In the remaining 2, the difference was barely large enough to be statistically significant. The largest effect attributable to glue line breaks was a small reduction in modulus in 4 of the 20 samples. Three of these were samples from the atmospheric spruce pulp.

Fracture Type - Most fibers broke in such a way that the fracture surface was roughly perpendicular to the axis of the fiber, but many also underwent a tearing type of failure that resulted in a larger fracture surface at an oblique angle to the axis. The degree to which this occurred in each case was estimated by measuring the length of the tear in terms of the fiber diameter. Analysis of the resulting values yielded significant correlation with breaking stress in only 4 samples. Three of these were spruce and showed a positive correlation: fibers that tore tended to be stronger. The other was a pine sample and the correlation was negative.

Load-Elongation Curve Parameters

Breaking Load and Stress - The mean breaking loads are shown in Table IV. The most noticeable effect is that of species, as might be expected, given the much larger CSA of the pine fibers (Figure 1). Another significant effect is that of fraction mesh size, also to be expected on the basis of CSA differences. No pronounced effect of temperature is apparent.

The extent to which these differences in load can be attributed to CSA differences can be determined by examining the stress data in Table V. The superiority of the pine pulp in terms of breaking load is seen to be totally the result of CSA differences, since it disappears when the data are converted to breaking stresses. In fact, the strengths of the spruce fibers are slightly superior to those from pine.

Table IV. Mean breaking loads.

Species	Fiberizing Conditions	Fiber Sample	Whole Sample	14-Mesh Fraction	28-Mesh Fraction	48-Mesh Fraction
Spruce	Atmospheric	1	16.0	21.3	14.6	11.4
		2	14.1			
	120°C	1	14.1	25.3	15.9	8.0
		2	13.7			
	160°C	1	15.9	26.1	19.2	11.8
		2	16.1			
Pine	120°C	1	28.2	35.6	30.6	25.8
		2			33.3	

Notes: a. Figures shown correspond to arithmetic means of the logarithms of the observed fiber breaking loads.

b. Each of the means shown has a 95% confidence interval of plus or minus approximately 16%.

c. Two means differ significantly if the larger is more than 25% greater than the smaller.

Table V. Mean breaking stress, kg/mm^2.

Species	Fiberizing Conditions	Fiber Sample	Whole Sample	14-Mesh Fraction	28-Mesh Fraction	48-Mesh Fraction
Spruce	Atmospheric	1	87	97	88	75
		2	84			
	120°C	1	76	108	80	55
		2	82			
	160°C	1	95	114	103	91
		2	82			
Pine	120°C	1	85	78	81	77
		2			88	

Notes: a. Figures shown correspond to arithmetic means of the logarithms of the observed breaking stresses.

b. Each of the means shown has a 95% confidence interval of plus or minus approximately 14%.

c. Two means differ significantly if the larger is more than 21% greater than the smaller.

Marked differences can be seen between average strengths of fibers from different size fractions of the same pulp. This is expected under the hypothesis that native fiber strength retention is inversely related to the energy input required to overcome the resistance to fiber separation. Fiber fragments that appear in the shorter fractions have undergone more severe mechanical action than intact fibers and longer fragments in the longer fractions; they may therefore be expected to have undergone more weakening as a result.

An additional factor that probably contributes to the lower strengths of the shorter fractions is that they contain high proportions of fragments of fibers that were broken because they were weak in their native state. These fragments, like their parent fibers, are relatively weak. This hypothesis is supported by the observation that the fibers and fragments in the shorter fractions are also relatively slender and therefore may be assumed to have originated mainly from earlywood, whose fibers are known to be weaker than those of latewood (2-5).

The effect of temperature is more apparent in the strengths of the classified fibers than in the whole pulps. The reason is that the whole pulp data suffer from an additional source of variation as a result of the marked difference between size classes. The average strength of fibers sampled from the whole pulp depends in a fortuitous way on the size composition of the particular set of fibers selected for testing. This was apparent in the variances of the individual data sets even though, as indicated in the footnotes to the tables, all variances were pooled for simplicity. Thus, in assessing the temperature effect, more weight should be assigned to the results obtained with classified fibers.

Such an assessment leads to the conclusion that fibers separated at 160°C are stronger than those separated at 120°C. This is in accord with the hypothesis presented in the introduction - that separation results in fiber weakening to an extent that is directly related to the prevailing resistance to separation. This suggests that conventional thermomechanical pulping sacrifices strength potential to achieve surface development. It follows that separation at higher temperatures than are conventionally used would produce a higher strength sheet if a way could be found to develop the bonding potential of the resulting fibers without decreasing their strength.

The lack of superiority of the 120°C fibers over those separated under atmospheric conditions may be seen as a flaw in the reasoning outlined above. It can, however, be explained on the basis of the smaller proportion of testable fibers in the atmospheric pulp (60% vs. 80% - cf. Table IX). Presumably the fibers that are absent because they were too small to test are weaker for the same reason that 48 mesh fibers are weaker than 28 mesh ones - damage in the refiner. Had it been possible to test them, it is reasonable to suppose that the average for the atmospheric pulp would have been decreased to the point where it was equal to or less than that for the 120°C pulp.

Breaking Strain and Initial Modulus - Average breaking strains ranged from 7-10%, being somewhat higher for fibers separated at 120°C than at the other two temperatures, and higher for spruce than pine (Table VI). For a given fiberization condition, strain, unlike stress, showed no systematic variation with average fiber size. Thus, within a series of Bauer-McNett fractions, strain remained constant, while stress decreased with decreasing average fiber size. For stress-strain curves that are approximately linear, it follows that the modulus must also decrease with decreasing fiber size, and this was observed to be the case, as Table VII shows. The implied correlation between stress and initial modulus may even be more general, as indicated by Figure 2.

Table VI. Mean breaking strain, %.

Species	Fiberizing Conditions	Fiber Sample	Whole Sample	14-Mesh Fraction	28-Mesh Fraction	48-Mesh Fraction
Spruce	Atmospheric	1	8.6	7.9	8.1	8.8
		2	8.3			
	120°C	1	7.7	9.3	9.0	9.3
		2	8.3			
	160°C	1	7.6	7.5	7.0	7.0
		2	9.9			
Pine	120°C	1	6.6	7.2	7.0	7.2
		2			8.1	

Notes: a. Figures shown correspond to arithmetic means of the logarithms of the observed breaking strains.
b. Each of the means shown has a 95% confidence interval of plus or minus approximately 10%.
c. Two means differ significantly if the larger is more than 14% greater than the smaller.

Table VII. Mean modulus, kg/mm^2.

Species	Fiberizing Conditions	Fiber Sample	Whole Sample	14-Mesh Fraction	28-Mesh Fraction	48-Mesh Fraction
Spruce	Atmospheric	1	980	1280	1130	880
		2	1120			
	120°C	1	620	1170	860	650
		2	990			
	160°C	1	1390	1790	1660	1410
		2	870			
Pine	120°C	1	1640	1310	1180	1090
		2			1100	

Notes: a. Figures shown correspond to arithmetic means of the logarithms of the observed modulus.
b. Each of the means shown has a 95% confidence interval of plus or minus approximately 15%.
c. Two means differ significantly if the larger is more than 14% greater than the smaller.

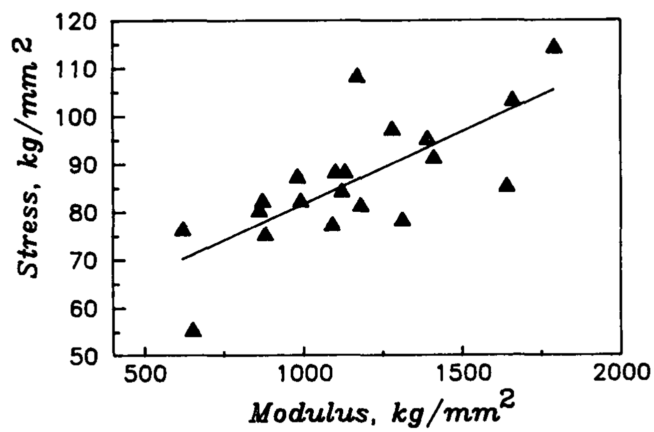

Fig. 2. Correlation between initial modulus and breaking stress.

Fibers from the 160° pulp had significantly higher modulus than those from the other pulps. This corroborates the observation of low breaking strain for these fibers.

<u>Unusually Strong Fibers</u>

Several of the fibers tested had extraordinarily high values of breaking stress and initial modulus. The most notable examples are shown in Table VIII. All were unusually slender, having CSA's well below the group averages. No explanation for the high strength of these fibers is currently available, but their occurrence suggests the existence of some factor other than those previously identified that can give very high strength values.

Table VIII. Extraordinary spruce fibers.

Fiberizing Condition	Fiber No.	Breaking Load, g	CSA, μm^2	Breaking Stress kg/mm^2	Initial Modulus, kg/mm^2	Breaking Strain, %
Atmospheric	M-606	35.8	85	421	4630	9.7
	M-638	12.3	29	427	5580	8.4
120°C	O-101	33.3	41	811	7500	10.1

EXPERIMENTAL DETAILS

The 300 CD refiner, which normally has both flat and conical refining zones, was fitted with 12 inch flat single rotating disc plates only. Experiments were conducted at 120 and 160°, and also under atmospheric conditions. For the runs at the higher temperatures, the chips were steamed at atmospheric pressure for approximately 15 minutes prior to passing through a 4:1 compression ratio screw feeder into the preheater, where they were retained at the appropriate temperature for 10-15 min before fiberizing. Deionized water was added at the feed screw to prevent burning of the pulp; the consistency calculated from the chip and dilution water flows was 16%.

Since the objective of the refiner runs was to produce fibers which had been just separated and not refined, power input to the primary refiner was kept low and the secondary was operated with a very wide plate gap. It did little or no refining and was used merely to pump the fiber out of the system.

In each case, pulp collection was begun after steady operation had been achieved. When a sample of sufficient size had been obtained, the run was interrupted and operating conditions were changed to produce pulps for another purpose. When these were completed, the operating conditions were returned as nearly as possible to their original values and pulp collection was begun again. The replicate samples generated in this way were separately analyzed and are identified in the data tables as samples 1 and 2 within each fiberizing condition. Within sets, the runs reproduced fairly well (Table IX). An inverse relationship was observed between temperature and energy consumption. This is to be expected, since fiber separation, not refining, dominates under these conditions. The resistance to fiber separation decreases as the temperature approaches and then surpasses the glass transition temperature of lignin.

Screening and Characterization - The coarse pulps were screened on a 0.006-inch cut laboratory flat screen. The accepts levels were roughly similar for the three sets of operating conditions, averaging 35-45% (Table IX). The decreased resistance to fiber separation at the higher temperatures was paralleled by an increase in fiber length, although the effect observed upon increasing the temperature from 120 to 160°C was small and was not apparent in Bauer-McNett classification data. The pulps fiberized under pressure had high average fiber lengths and low contents of material passing through a 100 mesh screen.

Preparation of Pine Pulp

Loblolly pine chips were steamed at 120°C for 2 min and then blown into an Asplund mill, where they underwent fiberization for 2 min at 120°C. The fiberization was carried out with 100 g batches of chips and the resulting batches of fiber were combined before screening on a 0.009-inch cut laboratory flat screen. Screening and classification data are included in Table IX.

Load-Elongation Testing

The procedures used for sampling, mounting and testing the fibers are those described by Hardacker (4,6). Epon 907 epoxy cement was used to attach the fibers to the mounting pins.

CONCLUSIONS

The fiber separation phase of mechanical

Table IX. Fiberization runs, screening, and classification.

Species	Nominal Fiberization Condition	Run	Preheater Temp., °C	Primary Refiner Plate Clearance, mm	Specific Energy Consumption HPD/ODT	0.006 Inch Cut Screen Accepts, %[a]	Fiber Length,[b] mm	% Retained on Screen of Mesh Size 14	28	48	100	Remainder, %
Spruce	Atmospheric	775-1	29	0.80	55.7	48.4	0.96	4	30	27	15	24
		775-2	57	0.80	48.0	34.4	1.26	7	37	31	13	13
		Average			51.8	41.4	1.11	6	34	29	14	17
	120°C	773-1	120	0.40	21.4	48.2	1.73	27	33	18	5	16
		773-2	121	0.40	22.6	42.1	1.68	24	37	21	6	12
		Average			22.0	45.1	1.70	26	35	20	6	14
	160°C	774-1	160	0.60	7.6	34.4	1.96	20	37	20	6	16
		774-2	160	0.60	10.2	36.1	1.76	22	43	20	7	9
		Average			8.9	35.2	1.86	21	40	20	6	12
Pine	120°C	1	120		n.d.[c]	63.9	n.d.	9	21	33	10	27
		2	120			67.5		8	22	34	8	27
		Average						8	22	34	9	27

[a] *Based on o.d. weight of pulp out of refiner.*
[b] Length-weighted average; analysis of Kajaani FS-100.
[c] n.d. = not determined.

pulping results in fiber weakening to an extent that is directly related to the prevailing resistance to separation. This suggests that conventional thermomechanical pulping sacrifices strength potential to achieve surface development. It follows that separation at higher temperatures than are conventionally used would produce a higher strength sheet if a way could be found to develop the bonding potential of the resulting fibers without decreasing their strength.

Fibers separated at 160°C are stronger than those separated at 120°C. This can be attributed to the smaller resistance to fiber separation at the higher temperature.

Marked differences can be seen between average strengths of fibers from different size fractions of the same pulp. Fiber fragments that appear in the shorter fractions have undergone more severe mechanical action and more weakening than intact fibers and longer fragments in the longer fractions. An additional factor that probably contributes to the lower strengths of the shorter fractions is that they contain high proportions of fragments of fibers that were broken because they were weak in their native state.

Compared to white spruce mechanical pulp fibers, those from loblolly pine are slightly weaker. They also differ from the spruce fibers inasmuch as their strength is similar in all size fractions.

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REFERENCES

1. VAN DEN AKKER, J.A., LATHROP, A.L., VOELKER, M.H., and DEARTH, L.R. Tappi 41(8):416 (1958).
2. LEOPOLD, B., and McINTOSH, D.C. Tappi 44 (3):235(1961).
3. McINTOSH, D.C., Tappi 46(5):273(1963).
4. HARDACKER, K.W., in The Physics and Chemistry of Wood Pulp Fibers. D.H. Page, ed. TAPPI, N.Y., 1970. p. 201.
5. PAGE, D.H., EL-HOSSEINY, F., WINKLER, K., and BAIN, R. Pulp Paper Mag. Can. 73(8): 72(1972).
6. HARDACKER, K.W., and BREZINSKI, J.P., Tappi 56(4):154(1973).
7. KERSAVAGE, P.C., Wood and Fiber 5(2):105 (1973).
8. PAGE, D.H., and EL-HOSSEINY, F., Svensk Papperstid. 79(14):471(1976).
9. PAGE, D.H., SETH, R.S., and EL-HOSSEINY, F. Transactions of the Eighth Fundamental Research Symposium held at Oxford, Sept., 1985, V. Punton, ed., Mechanical Engineering Publications Limited, London, 1985. Vol. 1, p. 77.
10. HARDACKER, K.W., Tappi 45(3):237(1962).
11. HARDACKER, K.W., Tappi 52(9):1742(1969).